Spatially resolved photoluminescence of inversion domain boundaries in GaN-based lateral polarity heterostructures

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Intentionally grown GaN inversion domain boundaries (IDBs) of lateral polarity heterostructures have been spectroscopically imaged at low temperature using high spatial resolution photoluminescence. It is shown that the IDBs are not only optically active, but are more than an order of magnitude brighter than the GaN bulk material. Our findings are in agreement with calculations predicting that IDBs should not adversely affect near-band-gap photoluminescence due to the absence of midgap electronic states. Typical linewidths are on the order of 10–20 meV, however, features less than 0.6 meV are observed. The boundary emission is found to be neither spectrally nor spatially uniform. Also, a strong polarization dependence of the IDB photoluminescence is measured and determined to be oriented parallel to the boundary between GaN of N- or Ga-face polarity. [DOI: 10.1063/1.1390486]

The group-III nitrides are leading candidates for the fabrication of shorter-wavelength optoelectronic devices.[1] These semiconductors emit over a wide range of energies, with the room-temperature direct-band gaps of InN, GaN, and AlN equal to 1.9, 3.42, and 6.2 eV, respectively. Most group-III nitride devices on the market today, whether they be green and blue light-emitting diodes (LEDs) or long lived (>10 000 h) multiple-quantum-well lasers, are fabricated with InGaN rather than GaN itself.[2] It is believed that the addition of In into GaN creates radiative traps[3] that effectively localize the carriers before they diffuse to threading dislocations, which have been shown to be nonradiative recombination centers.[4] These optically active traps are needed for bright devices since dislocation densities are extremely high in GaN due predominantly to the unavailability of lattice-matched substrates, a problem that also manifests itself in the form of locally fluctuating strain and electric fields. The downside of using InGaN as the active layer is that it restricts the operation of devices to emission energies below the GaN band gap. In order to produce better devices from pure GaN, most research has been directed towards the growth of low dislocation density, low strain material using techniques such as lateral epitaxial overgrowth (LEO),[1,5] pendeoepitaxy,[6] and homoepitaxy.[7,8] Meanwhile, relatively little investigation has gone into the formation of local radiative traps in GaN that do not significantly lower photon energies. It is along this line that we present spatially resolved photoluminescence data demonstrating that shallow, optically active traps exist at inversion domain boundaries (IDBs) of wurtzite GaN.

The inversion domain boundaries studied here were created by epitaxial growth of GaN-based lateral polarity heterostructures using plasma-induced molecular-beam epitaxy (PIMBE) on a patterned $AlN/c-Al_2O_3$ substrate. By high-resolution x-ray diffraction and atomic-force microscopy the structural as well as the surface morphology of GaN with Ga-face polarity (grown on an AlN nucleation layer) was found to be of much higher quality in comparison to the N-face material (grown directly on c-Al_2O_3) grown at the same time on the same wafer. More detailed information about the growth and characterization of lateral polarity heterostructures can be found in Ref. 9.

The boundary region of interest here, between a pair of GaN stripes with opposite (Ga- or N-face) polarity, is an IDB. The IDB planes in these samples are perpendicular to either the $\langle 10\underline{1}0\rangle$ or $\langle 1\underline{2}10\rangle$ direction of wurtzite GaN. The boundaries between GaN of different polarities were spectroscopically imaged in the far field using a laser scanning confocal UV microscope. The samples sit on a cold finger inside a liquid-helium, continuous-flow Janis microscope cryostat at a temperature of about 10 K. The 325 nm line of a He–Cd laser was used for cw excitation. We both excite and collect through a 0.75 NA, 63× Zeiss microscope objective that corrects for the spherical aberration encountered when passing through the sapphire window above the sample. Collected emission is focused through a pinhole, defining our spatial resolution, and dispersed inside a 1 m Spex grating monochrometer. The spectra are read with a liquid-nitrogen-cooled charge-coupled-device camera resulting in a three-dimensional data set (x,y,λ). The spectral resolution of the apparatus is less than 0.6 meV and the spatial resolution is diffraction limited to less than 400 nm.

The spectrum shown in Fig. 1(a) is an average of all the spectra acquired during the scan for Fig. 1(c) and is representative of a photoluminescence (PL) spectrum taken with a spatial resolution of 18 μm, rather than diffraction-limited spatial resolution. This spectrum is qualitatively similar to Fig. 1(b), showing that local features, like those to be discussed later, are drowned out by GaN bulk emission when performing low spatial resolution PL. Figure 1(b) is a typical spatially resolved spectrum of GaN with Ga-face polarity

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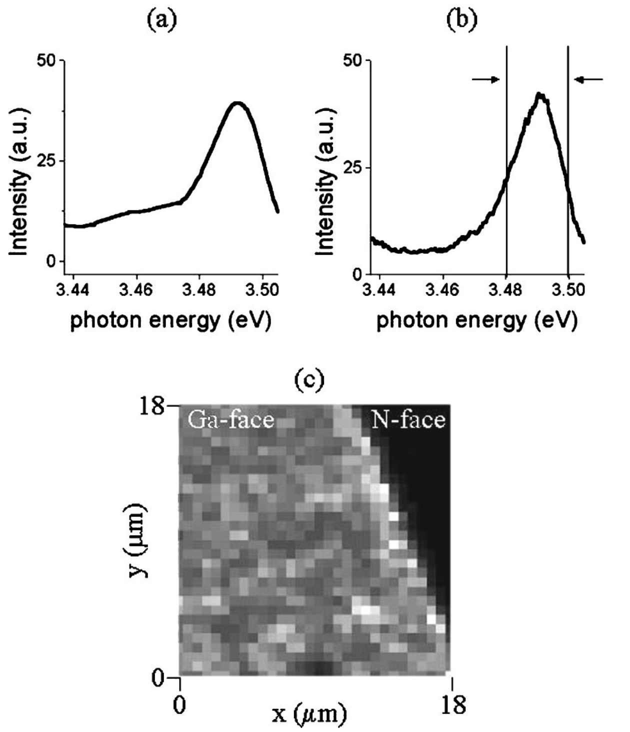

FIG. 1. (c) Two-dimensional, low-temperature photoluminescence image of intensity integrated between 3.48 and 3.50 eV. The emission in this energy range is dominated by the luminescence of GaN with Ga-face polarity. A typical spectrum from only the Ga-face region shown in (b). The spectrum shown in (a) is the average of all spectra from the scan, comparable to a spatially unresolved PL spectrum. The sharp lines on either side of (a) and (b) are spontaneous emission lines from the laser cavity.

from a diffraction-limited spot on the sample. In general, the PL from the Ga face is centered near 3.49 eV with a spectral width of approximately 20 meV. Both these values, however, fluctuate as a function of position, and it is not uncommon to see sharp spectral features (full width at half maximum <1 meV) at isolated spots. We also observe emission from the N-face material, but it is weaker, much broader, and centered around 3.4 eV. The relatively weak luminescence from this region is expected because the sample was grown under conditions optimizing the structural quality of the GaN with Ga-face, not with N-face, polarity.

Figure 1(c) is a two-dimensional PL image of the region adjacent to and including an IDB. It is an image of integrated emission from the spectral window between 3.48 and 3.50 eV [the energy range between the two lines in Fig. 1(b)]. The bulk Ga-face material emits strongly at this energy while the N-face material does not. It is revealed in Fig. 2(a), however, that the brightest features on the sample are the inversion domain boundaries themselves. Figure 2(a) is an image of integrated PL between 3.42 and 3.48 eV. We see that the boundary is optically active in the energy range associated with bound excitonic transitions. Even when our entire spectral range (3.42–3.50 eV) is considered, the PL from the IDB is, on average, more than an order of magnitude brighter than emission from the bulk Ga-face material, as seen in Fig. 2(b).

Closer examination of the IDB PL shows that emission from the boundary is neither spatially nor spectrally uniform. Instead, we observe an array of local emitters aligned along the boundary. Three spectra from three different positions along the IDB are shown in Fig. 3. The spectra shift and

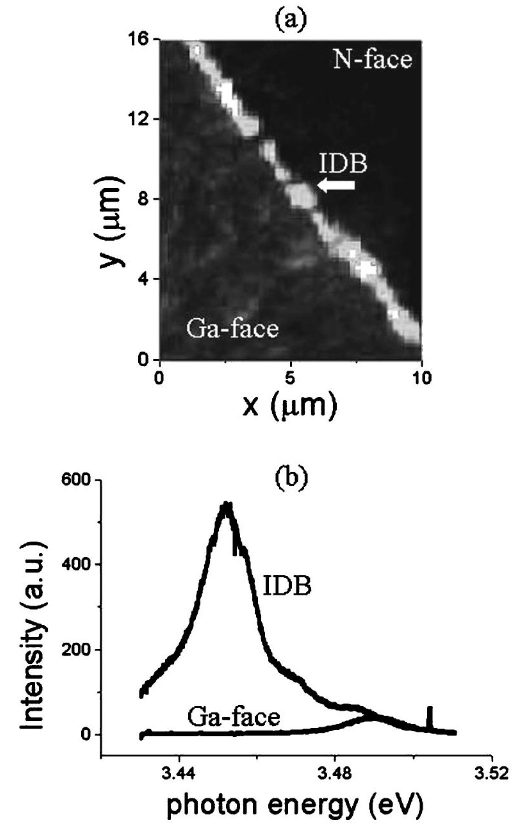

FIG. 2. Two-dimensional integrated intensity image of PL with photon energies between 3.43 and 3.48 eV, dominated by emission from the IDB, is shown in (a). Ga-face material is on the lower-left side of the image while N-face material is on the upper right. The spectra in (b) illustrate the relative PL intensities of an IDB and bulk GaN with Ga-face polarity.

change shape from point to point, and narrow features, limited in width by instrument resolution, appear at various locations. In general, boundary spectra look like Fig. 3(b) with peak emission centered near 3.45–3.46 eV. This is 30–40 meV lower in energy than the bulk Ga-face luminescence, which means the boundary PL we observe originates from some type of shallow trap. We also note that the intense emission from the boundary is not obvious when the PL is

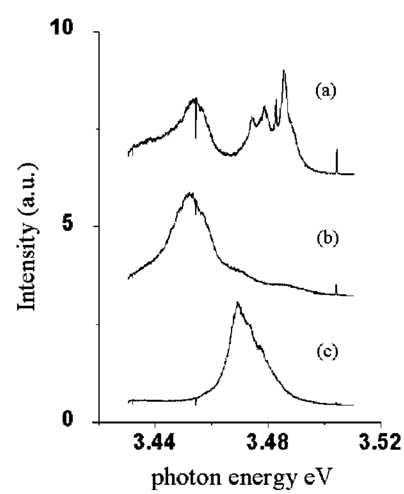

FIG. 3. These three spectra from separate points along the IDB illustrate the spectral inhomogeneity of the boundary emission. Narrow features, like those in (a), are observed intermittently. Typical IDB spectra look most like (b) and are centered 30–40 meV below the peak emission energies of bulk GaN with Ga-face polarity.

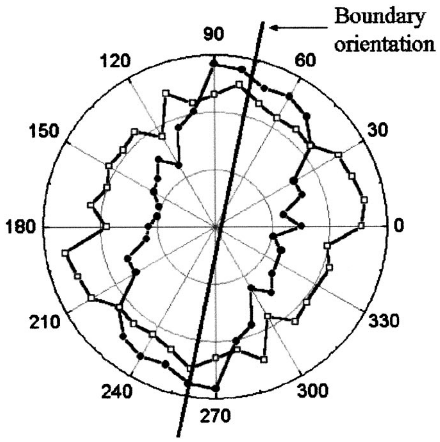

FIG. 4. Average polarization of IDB photoluminescence, shown by the closed circles, is oriented parallel to the boundary. There appears to be no obvious polarization dependence of emission from the bulk GaN with Ga-face polarity (open squares).

averaged over an $18\times18\,\mathrm{um}^2$ square region, as in the spectrum shown in Fig. 1(a). The emission of Ga-face GaN dominates the integrated spectrum because the surface area of the Ga-face region is large relative to that of the IDB, which defines a line where it intersects the surface. This emphasizes the importance of high spatial resolution when performing spectroscopy on micropatterned samples.

Bright emission from the IDB itself was unexpected since analogous structures in zinc-blende III–V materials are known to be nonradiative recombination centers.[10] Northrup and co-workers present first-principles calculations of domain-wall energies for IDBs in GaN, along with possible lattice structures for IDBs in the $\{10\bar{1}0\}$ and $\{1\bar{2}10\}$ crystalline planes.[11,12] It was predicted that IDBs in wurtzite GaN would *not* induce electronic states in the band gap, implying IDB structures should not adversely affect PL efficiency. Our findings support these predictions and further indicate that IDBs are shallow, optically active traps that can function as bright emission centers.

Along with being relatively intense, we found the IDB emission to be, on average, polarized parallel to the boundary. Our measured polarization ellipse (solid circles) is shown in Fig. 4. It has an ellipticity greater than 2 and is oriented along the boundary. Care was taken to correct for the polarization dependence of the beam splitters and grating. We measured no polarization dependence for the emission of GaN with Ga-face polarity (open squares in Fig. 4), as expected. This is an important experiment as it demonstrates that the luminescence we observe at the boundary comes from a state associated with the IDB itself, and not states associated with the bulk.

The importance of local, radiative centers to the fabrication of optoelectronic devices has already been established by the success of InGaN LEDs and lasers. Our findings have considerable implications regarding GaN devices. In particular, IDBs in GaN are shallow, radiative traps. This work underlines the need for further experimental and theoretical investigation into the optical properties of inversion domain boundaries. We speculate that the incorporation of IDBs into GaN (for example, by patterning arrays of boundaries) could lead to strongly emitting GaN-based UV devices.

In conclusion, GaN IDBs are shown to be bright, optically active traps. These emission centers are over an order of magnitude more intense and 30–40 meV lower in energy than emission from the bulk material. The IDB PL is both spatially and spectrally inhomogeneous and observed to be strongly polarized parallel to the boundary.

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